ENERGY AND PARTICLE TRANSPORT MODELING FOR THE TOKAMAK EDGE/SOL REGION*

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Understanding and developing validated models of energy and particle transport through the scrape-off layer (SOL) of tokamak devices is central to the design of larger machines. Important issues include having an acceptable power load on material surfaces, controlling edge profiles for plasma stability and impurity shielding, and helium removal. In this paper, we focus on developments both in modeling detached divertor operation in the DIII-D and Alcator C-Mod tokamaks with the integrated 2-D transport code UEDGE and in more detailed analysis of specific aspects of the transport problem. Topics include attached/detached divertor operation with impurities, origin of SOL turbulence, electrostatic potential description across the separatrix, and plate sheath current-voltage characteristics that lead to a method for broadening the SOL.

The DIII-D and Alcator C-Mod tokamaks provide diverse conditions for model validation. DIII-D has an open divertor with numerous diagnostics, highlighted by the new divertor Thomson scattering measurements of the electron density, n_e, and temperature, T_e, giving 2-D divertor-leg profiles. In addition, we compare Thomson n_e and T_e profiles near the midplane, IRTV divertor heat flux, H_α line emission, and impurity emissions in the VUV. Alcator C-Mod has a more closed divertor with a highly inclined divertor plate and operates at higher plasma densities. Here we compare with plate values of n_e and T_e from Langmuir probe arrays and radiated power from bolometer arrays.

We present two types of UEDGE simulations of these devices: qualitative with fixed anomalous diffusion coefficients (D for n and $\chi_{e,i}$ for energies), and quantitative where D and $\chi_{e,i}$ are changed to fit individual discharges. UEDGE includes classical transport along **B** and anomalous in the radial direction on a nonorthogonal mesh with a parallel Navier-Stokes fluid neutral model which couples to the ion parallel flow via charge exchange. Cross-field neutral transport is diffusive from charge-exchange and neutral-neutral collisions which effectively transports momentum and energy radially. Volume recombination is important for detachment and thus included. Experimentally, detached plasmas (low energy and particle fluxes) often occur at the inner divertor plate and can be induced at the outer plate by injection of deuterium or impurity gas; excessive injection leads to a MARFE on the closed flux surfaces and deterioration of confinement. We show this same behavior from UEDGE simulations. For pure deuterium plasmas, scans from high-to-low input power show progressively that the inner plate plasma becomes detached first, then the outer leg detaches, leading to a broad $T_e \sim 1$ eV region develops below the x-point, and finally a cold, high density MARFE forms within the separatrix. With the tilted plate, Alcator C-Mod simulations show a remnant attached plasma along the top "nose" of the outer plate. The effect of intrinsic carbon impurity radiation, described with either a fixed-fraction model or multispecies model, is

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similar to input power reduction. The plate power naturally decreases and a substantial reduction of ion flux to the plate occurs from plasma recombination.

Detailed simulations of 10 DIII-D discharges that include comparison with the divertor Thomson scattering have been done by adjusting the D and $\chi_{e,i}$ to fit the midplane profiles, yielding $\chi's$ in the range of 0.1 to 1.4 m^2/s for a range of parameters with D being 1/2 to 1/3 smaller. Improved fits to the bolometer measurements are found with the multispecies impurity model. The H_α signal fits well except for cords through the private flux region which is being investigated with the DEGAS neutral Monte Carlo code. Detailed Alcator C-Mod simulations show that at the outer strike-point, heat flux and current drop by an order of magnitude as 0.5% of carbon is introduced to induce partial detachment. The amount of carbon radiation and $T_e \sim 1$ eV up to the plate "nose" agree well with experimental values. We also show time-dependent simulations of the DIII-D SOL during a disruption which requires D and $\chi_{e,i}$ of ~ 20 m^2/s, and present a model for radiation transport near an ablating plate that includes the radiation to the side walls.

Coupling between the SOL and core is modeled using the CORSICA-2 code. Here the 1-D core transport and the 2-D UEDGE SOL transport are self-consistently coupled through the density and temperature variables at a boundary inside the separatrix. We show the response of the core and SOL to a (forced) L-H transition for DIII-D and an improved self-consistent, semi-empirical model. We report on coupled studies of attached/detached transition of divertor plasmas and neutral gas core penetration.

Fundamental studies of SOL turbulence are performed by 3-D electrostatic fluid simulations that include the edge and SOL regions with a quasi-ballooning coordinate representation. The four-field plasma model for n_e, vorticity, parallel ion velocity ($v_\parallel$), and T_e is is used. Instability drives include the conducting-wall mode, radial and axial shear in $\mathbf{E} \times \mathbf{B}$ velocity, field-line curvature, and radial gradients in $v_\parallel$. For attached, low-recycling divertor plasmas with n_e and T_e uniform, the fluctuations are roughly constant along $\mathbf{B}$, and for typical DIII-D parameters, give diffusivities of ~ 2 m^2/s. For the detached-like plasmas T_e drops a factor of 50 to the plate and n_e increases a factor of 5. For simulations with no magnetic shear, the fluctuation levels are about 50% larger than the attached case at the midplane, but are strongly reduced at the plate. The larger amplitude at the midplane and a bigger phase shift between potential and density fluctuations gives a midplane diffusivity an order of magnitude larger, while the diffusivity at the plate is much smaller than in the attached case. We present results from a new model for x-point shear effects. For the parameters of detached plasmas in DIII-D, part electrostatic, part electromagnetic versions of the conducting wall and axial shear modes are required, and we give an analytic theory of their stability.

We present a model of the equilibrium electrostatic potential, ϕ, that applies to both closed and open B-field regions. The key change to UEDGE is obtaining the radial current from an angular momentum transport equation, instead of the previous mobility model. Parallel transport is classical, and radial transport is anomalous, having diffusive and Reynolds stress contributions. Charge exchange with the gas is also included. The model correctly gives the change from positive to negative electric field in moving from the SOL to the core edge and affects $\mathbf{E} \times \mathbf{B}$ flows near the plates.

To properly close the set of equations describing plasma behavior in the SOL, we have formulated the current-voltage characteristics (CVC) of the plate sheath including electric drifts and diamagnetic currents; both the plasma equilibrium and fluctuation effects are included. The form of the CVC expression suggests a novel technique for broadening the width of the SOL by producing toroidally asymmetric ϕ variations leading to convective-cell transport. Such potential variations could be produced by: i) wavy divertor plates; ii) biasing segments of the plates; iii) plate segments with different secondary emission coefficients; and iv) toroidally asymmetric multi-point gas-puff. The fourth can work even when the plasma is fully detached from the divertor plates. The strong convection is limited to the SOL, and by proper selection of the period of toroidal variations, can be concentrated in the divertor-leg region.